



Torque Production in a Halbach Machine

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Summary

The NASA John H. Glenn Research Center initiated the investigation of torque production in a Halbach machine for the Levitated Ducted Fan (LDF) Project to obtain empirical data in determining the feasibility of using a Halbach motor for the project. LDF is a breakthrough technology for "Electric Flight" with the development of a clean, quiet, electric propulsor system. Benefits include zero emissions, decreased dependence on fossil fuels, increased efficiency, increased reliability, reduced maintenance, and decreased operating noise levels. In addition to meeting NASA goals and enabling new missions, this technology also has high potential for spin-off applications in military and civilian vehicles, as well as in commercial and industrial power equipment. A very high efficiency motor is essential for the success of LDF. The motor must have high power density (based upon mass and volume), low power requirements, excellent low temperature performance, high reliability, low maintenance, and long life. The motor must be compatible with a power source such as a Proton Exchange Membrane (PEM) fuel cell.

A commercial permanent magnet (PM) brushless motor rotor was tested with a custom stator designed and developed for this purpose. A new unique Halbach rotor was designed and developed to fit directly into the same stator and tested. The Halbach rotor consists of a series of high strength neodymium iron boron sector magnets. The magnets are oriented at ninety degrees to the adjacent magnet. This configuration cancels the magnetic field on the inside of the rotor and strengthens the field on the outside of the rotor. A direct comparison of the commercial rotor and the Halbach rotor was made and reported upon in this report. In addition, various test models were designed and developed to validate the basic principles described, and the theoretical work that was performed. The report concludes that the implementation of a Halbach rotor in a permanent magnet brushless motor can provide significant improvements in electric motor performance and reliability.

Introduction

The NASA Glenn Research Center has a wealth of experience in Halbach motor technology through the Fundamental Aeronautics Program. The goals of the program include improving aircraft efficiency, reliability, and safety. The Halbach machines tested for torque production were developed under the Fundamental Aeronautics Program.

The electromagnetic concept uses permanent magnet elements attached to the circumference of the rotor, and wire coils placed in the stator shell. The permanent magnets are arranged in a "Halbach" configuration which results in the cancellation of the magnetic field inside the rotor and a reinforcement of the magnetic field production outside the rotor, in the vicinity of the stator coils. This magnetic array configuration was pioneered by Klaus Halbach for use in particle accelerators (ref. 1). The advantages of this technique include high power density (based upon mass and volume), low power requirements, excellent low temperature performance, high reliability, low maintenance, and long life.

Theoretical derivations have been developed to predict the propulsion forces generated by a circular Halbach array and coil assembly. Finite element analyses were performed to validate the theoretical derivations. Experimental hardware was successfully designed and developed which served to validate the basic principles described and the theoretical work that was performed.

In addition to aircraft engines, this technology has potential application in ultra-efficient motors, computer memory systems, instrumentation systems, medical systems, manufacturing equipment, and space power systems, such as generators and flywheels.

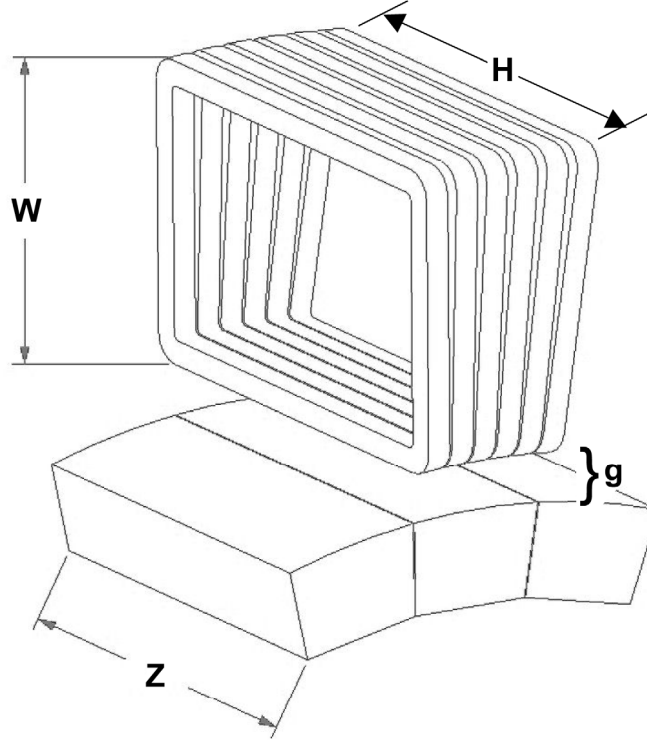


Figure 1.—A 6-turn r-z stator winding viewed from one end of the magnet array. The azimuthal span of the winding matches the width of one magnet. H and W refer to the winding height and width, respectively. A gap, g, exists between the center of the nearby conductors of the winding and the magnet surface.

Analytical Model of Motor Torque

As previously reported (ref. 2), a useful property of the radial Halbach array is that the radial (r) and azimuthal (ϕ) B field components are sinusoidal as a function of angular position (ref. 2). The peak instantaneous torque for the Halbach rotors occurs when the rotor angular position and drive current synchronize so as to produce the highest force on the stator winding in the azimuthal direction. See figure 1 for a diagram of a radial Halbach array with an r -z stator winding.

The r component of the B field will produce the Lorentz force on the winding and an equivalent opposing force on the magnet array in the opposite direction. The r component of the field is given by

$$B_r(r, \phi) = B_o \left(\frac{r_2}{r_2 + g} \right)^{p+1} \cos(p\phi) \quad (1)$$

where B_o is the field strength at the outer radial surface of the Halbach array, r_2 is the outer radius of the Halbach array, g is the total gap between the outer Halbach radius and the center of the top layer of stator conductors, and p is the number of Halbach pole pairs. For a 90° Halbach array of N_m magnets

$$p = \frac{N_m}{4} \quad (2)$$

from these expressions the peak instantaneous Lorentz torque becomes

$$T = wN_t I L B_o \left(\frac{r_2}{r_2 + g} \right)^{p+1} r_{cm} \quad (3)$$

where w is the winding factor the accounts for the sinusoidal roll-off of the field strength versus the spatial position of individual conductors in the winding, N_t is the total number of stator winding turns, L is the axial length of the winding and r_{cm} is the radial location of the centroid of the magnets.

For the commercial PM motor (not a Halbach) the field strength was predicted and measured to be approximately one-half of the Halbach rotor. Equation (3) is therefore valid with the substitution of $B_o/2$ for B_o .

Test Objectives

The objective of testing the Halbach machines is to validate the derived theoretical analyses and associated finite element analyses. This validation provides confidence in using the derived and numerical analyses for developing and optimizing conceptual Halbach motor designs.

Testing of the Halbach machines was performed at the NASA Glenn Research Center. Of particular interest is the performance of the machines. Torque, voltage, current, and temperature were monitored at various rotor operating conditions.

Test Hardware Description

Three Halbach Machine Test Models were developed. One test model includes a four inch long by 4 in. nominal diameter rotor as shown in figure 2, the second model includes a 1 in. long by 1 in. nominal diameter rotor as shown in figure 3, and the third model compares a commercial permanent magnet conventional rotor and a unique Halbach rotor and is shown in figure 4. The Halbach Machine Test Model block diagram is shown in figure 5. The Test Model components are identified in figure 6. This test hardware includes the support structure, the stator positioning system, and the torque measurement system.



Figure 2.—Four inch Halbach machine test model.

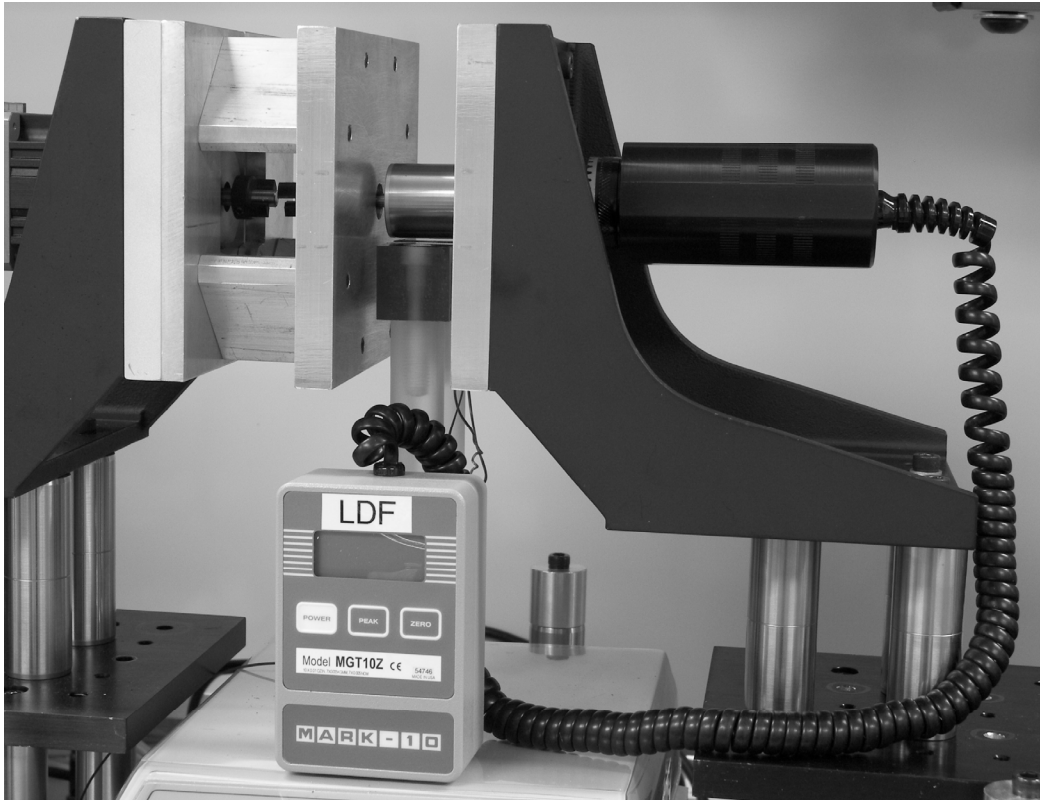


Figure 3.—One inch Halbach machine test model.

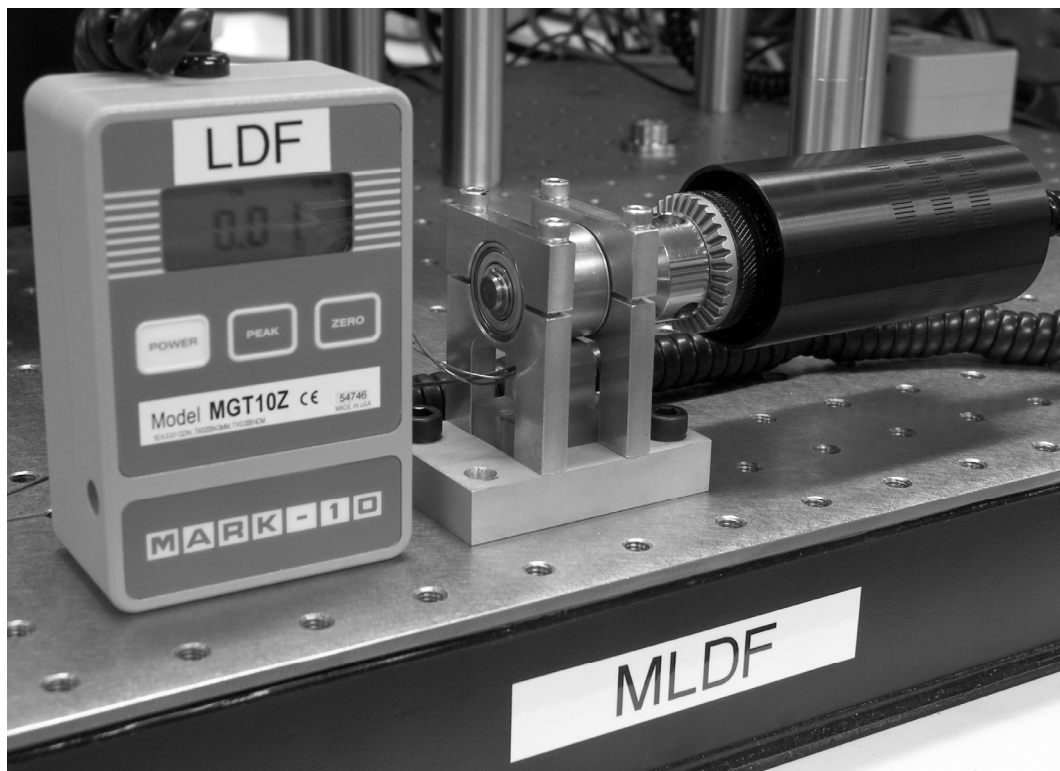


Figure 4.—Polyscientific Halbach machine test model.

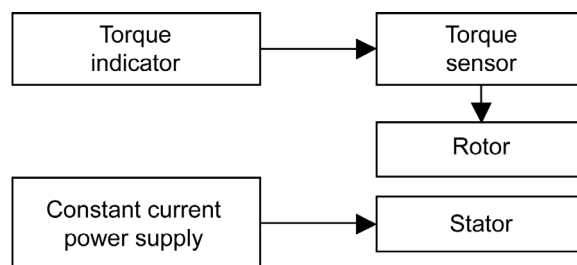


Figure 5.—Halbach machine test model block diagram.

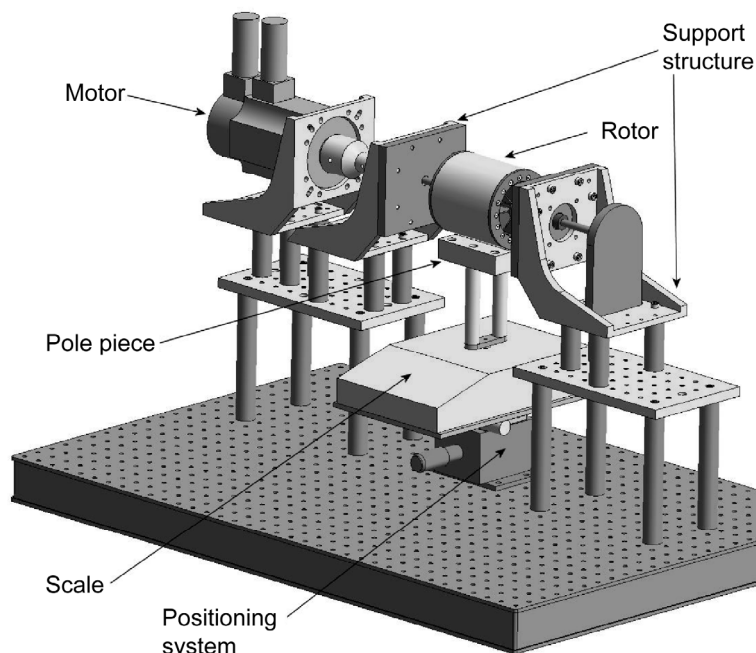


Figure 6.—Halbach machine test model components.

The support structure consists of precision structural components that are securely fastened to a heavy optics plate. The bearing blocks are connected to right angle brackets that are connected to the optics plate via posts. This subsystem supports and aligns the rotor with respect to the stator pole piece and positioning system that is placed on the optics plate.

The 4 in. test model consists of a 4 in. diameter rotor that is supported by two roller bearings secured in the bearing blocks. The rotor assembly is clamped to a 3/8 in. diameter drive shaft between the two bearings and is driven by the torque measurement system. The 1 in. test model system has a similar arrangement except that the rotor is connected to a 5 mm shaft. The 1 in. rotor assembly is pinned to the drive shaft and is also located between the two bearings.

The 4 in. rotor assembly, as shown in figures 7 and 8, has an overall diameter of 4.15 in. and an overall length (not counting the 2 1/2 in. clamping rings) of 4.31 in. The outer layer of the rotor consists of a 0.070 in. thick 300 series stainless steel shroud that is used to contain the 128 Neodymium Iron Boron B55 magnets. The magnets are 1/8 in. thick by 1 in. long segments. There are 32 segments around the circumference oriented in a Halbach array to make a ring and there are four rings total along the length of the rotor. The outside diameter of the magnet ring is 4 in. and each magnet segment occupies 11.25° of the assembled magnet ring. The magnets have a light press fit between the shroud and the hub that was wire electrical discharged machined from 6061-T6 aluminum. The hub has 32 flat surfaces machined around the circumference to support the back side of the magnets which is flat. The magnets are held in the rotor axially by two aluminum endplates fastened to the hub with non-magnetic stainless steel screws. Total weight of the assembled rotor is 6.2 lb (2.8 kg).



Figure 7.—Halbach rotor.

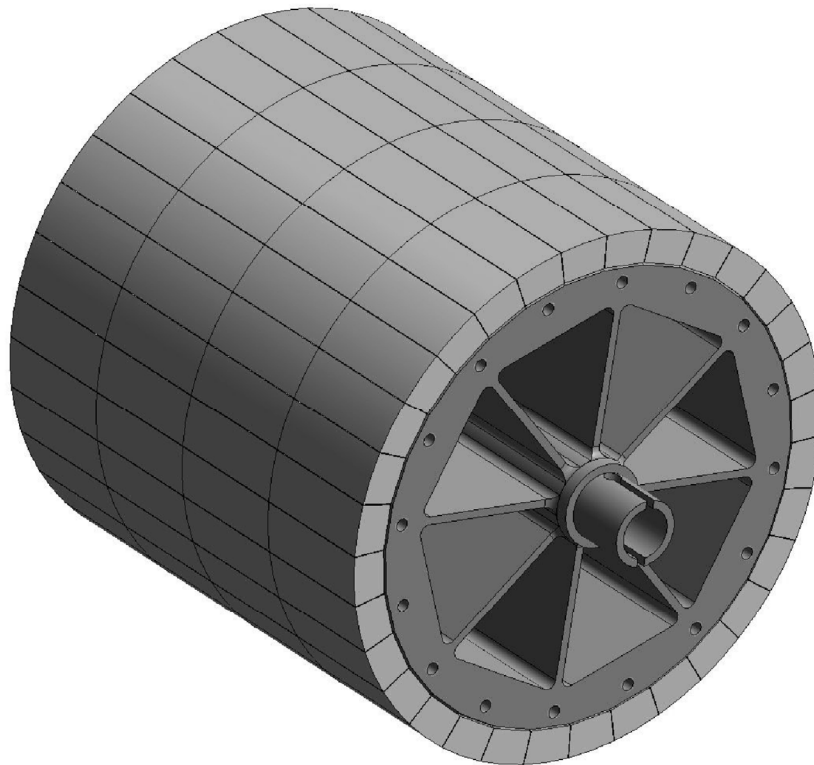


Figure 8.—Internal view of Halbach rotor.

The 1 in. rotor assembly has an overall diameter of 1.06 in. and an overall length of 1.14 in. The outer layer of the rotor consists of a 0.030 in. thick 300 series stainless steel shroud that is used to contain the 16 Neodymium Iron Boron B55 magnets. The magnets are 1/8 in. thick by 1 in. long segments. There are 16 segments around the circumference oriented in a Halbach array to make a ring. The outside diameter of the magnet ring is 1 in. and each magnet segment occupies 22.5° of the assembled magnet ring. The

magnets have a light press fit between the shroud and the hub that was wire electrical discharged machined from 6061-T6 aluminum. The hub has 16 flat surfaces machined around the circumference to support the back side of the magnets which is flat. The magnets are held in the rotor axially by two aluminum endplates fastened to the hub with non-magnetic stainless steel screws. Total weight of the assembled rotor is 0.21 lb (94 g).

Two Polyscientific rotors were tested. The first was the rotor that was in the purchased commercial motor. The second rotor was fabricated to contain 16 Neodymium Iron Boron B55 magnets around the rotor circumference oriented in a Halbach array to make a ring. The magnets are 1/8 in. thick by 1/2 in. long segments. The outside diameter of the magnet ring is 0.955 in. and each magnet segment occupies 22.5° of the assembled magnet ring. Both rotor assemblies have an overall diameter of 1.003 in. and an overall length of 0.518 in. The outer layer of the fabricated rotor consists of a 0.024 in. thick 300 series stainless steel shroud that is used to contain the magnets. The shroud was machined with one end closed, except for an opening for the shaft, to contain the magnets axially on one end. The magnets have a light press fit between the shroud and the hub that was machined from 6061-T6 aluminum. The hub has 16 flat surfaces machined around the circumference to support the back side of the magnets which are flat. The hub also has a disk machined on one end to support the magnets in the axial direction. The total weight of the assembled rotor, including the shaft, is 0.20 lb (89 g).

A test fixture was designed to support both the commercial and fabricated Polyscientific rotors. Since the fabricated rotor was designed to have the same dimensions as the commercial rotor, both rotors could be tested with this fixture. The commercial rotor assembly included the bearings pressed onto the shaft. The fabricated rotor has bearings that are held onto the shaft with a retaining ring. The rotor assembly is held into the fixture by clamping the bearings between two semi-circular holders.

DC current is applied to the stator pole piece to develop a magnetic field to react with the magnetic field of the rotor which produces a torque. Three different stator pole pieces were tested; the 4 in. *r-z* pole piece which has 20 turns of wire; the 1 in. *r-z* pole piece has 6 turns of wire; and the Polyscientific *r-z* pole piece which has 10 turns of wire. A typical *r-z* pole piece is shown in figure 9. The 1 in. pole pieces has 20 gauge square copper magnet wire, and the 4 in. pole piece and the Polyscientific pole piece have

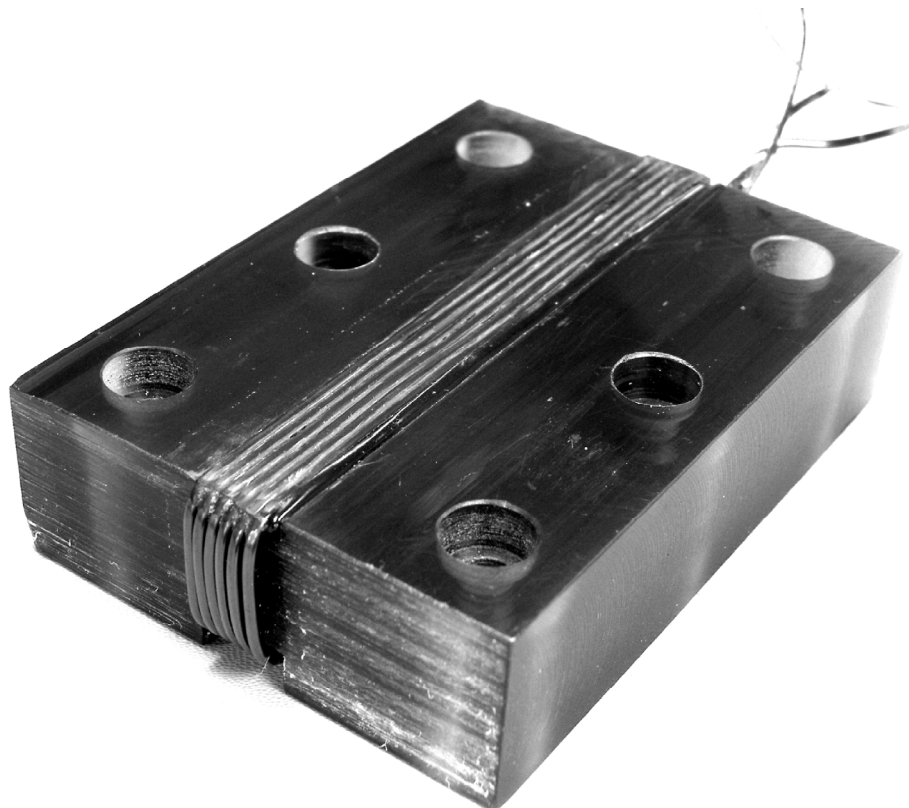


Figure 9.—Halbach magnetic test model *r-z* stator pole piece.

24 gauge square copper magnet wire. The wire is wound around a slot in the pole piece machined from Ultem polyetherimide with a maximum operating temperature of 340 °F. The magnet wire is cemented in place in the slot to ensure that accurate data is obtained.

The orientation of the pole piece is highly critical. For the 4 in. and 1 in. test models, the pole piece is connected with nylon fasteners to a precision horizontal linear stage which is then connected to a precision vertical stage. These two stages allow for an accurate adjustment of the coil placement in close proximity to the surface of the rotor. The Polyscientific test model has a fixed stator pole piece. The rotation of the Halbach array adjacent to the pole piece assembly generates a torque which is measured on the torque measurement system.

Instrumentation

The Halbach Machine Test Model was instrumented to measure machine performance. Test data were sent to the various test instruments and monitored. Test data included stator pole piece voltage, stator pole piece current, stator pole piece torque, stator pole piece temperature, and ambient temperature.

A block diagram of the instrumentation system is shown in figure 10. Type K thermocouples were used for all temperature measurements. Hall Effect transducers were used for all current measurements.

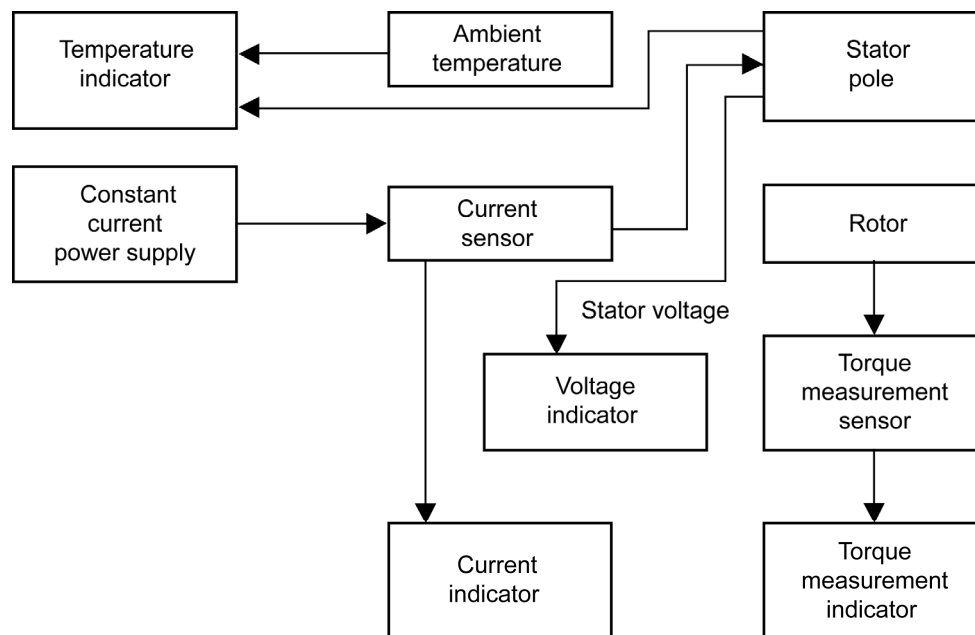


Figure 10.—Radial Halbach instrumentation block diagram.

Test Procedures

The tests described in this report were conducted at the NASA Glenn Research Center in Cleveland, Ohio. The tests were conducted in accordance with the test matrix provided in table 1.

Table 1.—Halbach Machine Test Matrix

Rotor	Stator	Gap (in.)	Current (ADC)
4 in. Halbach	20 turn <i>r-z</i>	0.050, 0.080, 0.110	1, 5, 9
1 in. Halbach	6 turn <i>r-z</i>	0.010, 0.025, 0.040	1, 5, 10
Polyscientific commercial	10 turn <i>r-z</i>	0.017	1, 5, 10
Polyscientific custom Halbach	10 turn <i>r-z</i>	0.017	1, 5, 10

The test procedure used four different rotor designs: 4 in. Halbach, 1 in. Halbach, Polyscientific commercial, and Polyscientific Halbach. Three different stator designs were used: 4 in. 20 turn *r-z* plane, 1 in. 6 turn *r-z* plane, and Polyscientific 10 turn *r-z* plane. The 1 in. stator contains 20 AWG square wire ($d = 0.032$ in. (0.8 mm)). The 4 in. and Polyscientific stators contain 24 AWG square wire ($d = 0.020$ in. (0.5 mm)). The test consisted of precisely locating the stator beneath the magnet array such that the air gap was one of three selected values for the 4 in. and 1 in. rotors: 0.050 in. (1.3 mm), 0.080 in. (2.0 mm) and 0.110 in. (2.8 mm). Factoring in the thickness of the retaining cover plate and the finite radius of the conductor, the effective gap distances from the magnet surfaces to the center of the conductor were 0.096 in. (2.4 mm), 0.126 in. (3.2 mm) and 0.156 in. (4.0 mm), respectively. Currents of 1, 5, and 9 amps were applied to the 4 in. stator. Currents of 1, 5, and 10 amps were applied to the other stators. Rotor torque was measured with a precision torque sensor.

The analytical model presented in this article predicted expected values for torque. Predicted values were compared to the measured results. Additionally, the analytical model predicted power dissipation (P_d).

Finite element analysis (FEA) predictions were also compared to the analytical and measured results for torque. Maxwell 3D (Ansoft Corp., Pittsburgh, PA) was the software used to generate the FEA predictions.

Test Results

System Performance

Various tests were conducted to determine system performance, per table 1. Table 2 summarizes the results obtained for the 1 in. radial Halbach Test Model rotor, table 3 summarizes the results obtained for the 4 in. radial Halbach Test Model rotor, and table 4 summarizes the results obtained for the Polyscientific rotors, both commercial (non-Halbach) and the custom-made Halbach array. Note that the largest current tested was 9 ADC, not 10 ADC, for the 4 in. Test Model. FEA results were not computed for the Polyscientific rotors.

Table 2.—One Inch Halbach Machine Test Model Performance

Gap (in.)	B (T) at gap	1 ADC (meas)	1 ADC (pred)	1 ADC (FEA)	5 ADC (meas)	5 ADC (pred)	5 ADC (FEA)	10 ADC (meas)	10 ADC (pred)	10 ADC (FEA)
0.01	0.4480	0.0016	0.0009	0.0010	0.0039	0.0043	0.0031	0.0084	0.0087	0.0066
0.025	0.3930	0.0007	0.0008	0.0009	0.0034	0.0039	0.0028	0.0065	0.0078	0.0052
0.04	0.3450	0.0006	0.0007	0.0008	0.0032	0.0035	0.0025	0.0061	0.0070	0.0040

Table 3.—Four Inch Halbach Machine Test Model Performance

Gap (in.)	B (T) at gap	1 ADC (meas)	1 ADC (pred)	1 ADC (FEA)	5 ADC (meas)	5 ADC (pred)	5 ADC (FEA)	9 ADC (meas)	9 ADC (pred)	9 ADC (FEA)
0.05	0.458	0.057	0.041	0.046	0.199	0.205	0.207	0.353	0.370	0.386
0.08	0.404	0.048	0.037	0.029	0.178	0.184	0.190	0.308	0.331	0.342
0.11	0.357	0.036	0.033	0.031	0.165	0.165	0.149	0.283	0.296	0.260

Table 4.—Polyscientific Test Model Performance

Rotor	Gap (in.)	B (T) at gap	1 ADC (meas)	1 ADC (pred)	1 ADC (FEA)	5 ADC (meas)	5 ADC (pred)	5 ADC (FEA)	10 ADC (meas)	10 ADC (pred)	10 ADC (FEA)
Halbach	0.053	0.302	0.008	0.002	N/A	0.010	0.009	N/A	0.011	0.018	N/A
Commercial	0.034	0.180	0.006	0.001	N/A	0.009	0.001	N/A	0.014	0.001	N/A

Discussion

The objective was to verify the analytical induced torque model of the radial Halbach array presented in this article by comparing both measured results and FEA-predicted results. The analytical model effectively predicts induced torque, as does the FEA for the two rotors analyzed.

These results were obtained using a small-scale test model. Analyses have shown that the factors limiting performance of this model actually improve dramatically when the physical scale is increased by an order of magnitude. The available space for packaging stator windings increases, permitting the use of lower gauge wire (less R), a higher number of turns (more amp turns), or both.

Concluding Remarks

The NASA John H. Glenn Research Center has successfully designed, developed, analyzed, and tested a revolutionary Halbach Machine for the development of torque. The goals of the program include improving aircraft efficiency, reliability, and safety. The objective of this work is to develop a viable permanent magnet motor utilizing Halbach arrays for all-electric flight, and many other applications. This concept will help to reduce harmful emissions, reduce the Nation's dependence on fossil fuels and mitigate many of the concerns and limitations encountered in conventional aircraft engines. The Halbach Motor does not require superconductive systems as required in many other electric motor designs. The Halbach Motor is useful for very high speed applications where slip rings cannot be used including turbines, instrumentation, and medical applications.

Theoretical derivations have been developed successfully (ref. 2) to predict the torque forces generated by a circular Halbach array and coil assembly. Finite element analyses successfully validated the theoretical derivations. Empirical test results obtained from experimental hardware successfully validated the basic principles described, and the theoretical work that was performed. Of particular value, are the analytical tools and capability that were developed successfully under this project. Performance predictions can be made confidently for machines of various scales.

The test results were obtained using a small scale test model. The factors limiting performance of this model improve significantly when the physical scale is increased. This favorable balance results in less resistive heating and the larger size gives more thermal mass, as well as more surface area from which to radiate heat.

The report concludes that because of their vastly greater magnetic flux density, Halbach array based motors can provide significant improvements in rotational system performance and reliability. In addition to aircraft engines, this technology has potential application in ultra-efficient motors, computer memory systems, instrumentation systems, medical systems, manufacturing equipment, and space power systems, such as generators and flywheels.

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2. Eichenberg, Dennis J., Gallo, Christopher A., and Thompson, William K., "Development and Testing of a Radial Halbach Magnetic Bearing," NASA/TM—2006-214477, 2006.

Appendix A—Equipment Under Test Summary Data Sheet

1.0	Halbach Machine Test Model		
1.1	10 in.-oz Force Measurement System		
1.1.1	Type	Electronic Digital	
1.1.2	Capacity	7 Ncm (10 in.-oz)	
1.1.3	Resolution	0.005 Ncm (0.01 in.-oz)	
1.1.4	Accuracy	±0.5 percent of full scale ±1 digit	
1.2	50 in.-oz Force Measurement System		
1.2.1	Type	Electronic Digital	
1.2.2	Capacity	35 Ncm (50 in.-oz)	
1.2.3	Resolution	0.05 Ncm (0.05 in.-oz)	
1.2.4	Accuracy	±0.5 percent of full scale ±1 digit	
2.0	1 in. Rotor		
2.1	Diameter	2.69 cm (1.06 in.)	
2.2	Length	2.89 cm (1.14 in.)	
2.3	Weight	79 g (0.17 lb)	
2.4	Magnet Type	Neodymium Iron Boron B55	
2.5	Magnet Orientation	Halbach Array (32)	
2.6	Magnet Shape	Sectors	
3.0	4 in. Rotor		
3.1	Diameter	10.54 cm (4.15 in.)	
3.2	Length	10.95 cm (4.31 in.)	
3.3	Weight	2800 g (6.2 lb)	
3.4	Magnet Type	Neodymium Iron Boron B55	
3.5	Magnet Orientation	Halbach Array (16)	
3.6	Magnet Shape	Sectors	
4.0	Polyscientific Commercial Rotor		
4.1	Diameter	2.54 cm (1.000 in.)	
4.2	Length	1.20 cm (0.472 in.)	
4.3	Weight	38 g (0.084 lb)	
4.4	Magnet Type	Neodymium Iron Boron	
4.5	Magnet Orientation	8 Poles	
4.6	Magnet Shape	Sectors	
5.0	Polyscientific Halbach Rotor		
5.1	Diameter	2.55 cm (1.003 in.)	
5.2	Length	1.32 cm (0.518 in.)	
5.3	Weight	33 g (0.073 lb)	
5.4	Magnet Type	Neodymium Iron Boron B55	
5.5	Magnet Orientation	Halbach Array (16)	
5.6	Magnet Shape	Sectors	

6.0	6-turn 1 in. <i>r-z</i> Stator Pole Piece		
6.1	Wire	#20 Square Copper	
6.2	Inductance	1.75 μH	
6.3	Resistance	21.0 $\text{m}\Omega$	
7.0	20-turn 4 in. <i>r-z</i> Stator Pole Piece		
7.1	Wire	#24 Square Copper	
7.2	Inductance	38.90 μH	
7.3	Resistance	441.7 $\text{m}\Omega$	
8.0	10-turn Polyscientific <i>r-z</i> Stator Pole Piece		
8.1	Wire	#24 Square Copper	
8.2	Inductance	1.80 μH	
8.3	Resistance	63.1 $\text{m}\Omega$	

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13. ABSTRACT (Maximum 200 words) The NASA John H. Glenn Research Center initiated the investigation of torque production in a Halbach machine for the Levitated Ducted Fan (LDF) Project to obtain empirical data in determining the feasibility of using a Halbach motor for the project. LDF is a breakthrough technology for "Electric Flight" with the development of a clean, quiet, electric propulsor system. Benefits include zero emissions, decreased dependence on fossil fuels, increased efficiency, increased reliability, reduced maintenance, and decreased operating noise levels. A commercial permanent magnet brushless motor rotor was tested with a custom stator. An innovative rotor utilizing a Halbach array was designed and developed to fit directly into the same stator. The magnets are oriented at 90° to the adjacent magnet, which cancels the magnetic field on the inside of the rotor and strengthens the field on the outside of the rotor. A direct comparison of the commercial rotor and the Halbach rotor was made. In addition, various test models were designed and developed to validate the basic principles described, and the theoretical work that was performed. The report concludes that a Halbach array based motor can provide significant improvements in electric motor performance and reliability.				
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